Drag of square section tubes

Chris Letchford [a,b] and Matthew Mason [c]
[a]*Rensselaer Polytechnic Institute, Troy, NY, USA, letchc@rpi.edu*
[b]*University of Tasmania, Hobart, TAS, Australia,*
[c]*Risk Frontiers, Natural Hazards Research Centre, Macquarie University, Sydney, NSW, Australia, matthew.mason@mq.edu.au*

1 INTRODUCTION

Square section poles have common usage for supporting lights, hoardings and signs. While the wind loading of such shapes has been undertaken since the pioneering work of Flachsbart in the 1930's, the effect of wind direction, turbulence, and corner radius for large shapes (full scale) is a subject that has not received much attention. The present study was motivated by the pole manufacturing industry seeking to improve the input to their designs. This paper presents the results of a series of wind tunnel studies on 2 full-size square-section shapes; one sharp-edged, the other with corner radii, in 2 different turbulent flows for 2 wind directions. The results are compared with earlier studies and recommendations made for design drag coefficients.

2 BACKGROUND

Drag on sharp-edged bodies where separation is well defined is generally thought to be independent of wind speed (Reynolds No.), but curved surfaces are known to suffer from this dependency and testing of such shapes often needs to be conducted at full scale with design wind speeds to assure legitimacy of transferring results from model to prototype. The classic case is the drag on a circular cylinder, where a well-known drag crisis is observed at a Reynolds typically around $2 * 10^5$ producing much reduced drag above this value of Reynolds Number compared to below it.

Many structures of this type; poles, tubes, and cylinders, are employed in highway traffic control and AASHTO [5] has provided guidelines for estimating forces on such structures. Much of this data was based on early NACA studies [1, 2] or more recent commercial tests by manufacturers [3, 4]. Studies by Lee [9], Cheng et.al. [10], and Tamura et.al. [11] represent some of the few studies to investigate the effect of turbulence, angle of attack, and corner radius carried out in controlled testing where effects of blockage and end plates [6, 7] have been systematically addressed. These studies and the work of Saathoff and Melbourne [8] have all demonstrated the significant influence of turbulence on separating shear layers and subsequent reattachment to the sides of these shapes, even for zero angle of attach under certain conditions. This behaviour over a larger range of Reynolds Number is needed for providing better design information for industry and standards.

This study evaluates the drag on a basic square section tube and examines the effects of turbulence, angle of attack and corner radius at or near full scale Reynolds Numbers for typical traffic signal and luminaire structures. The wind tunnel and model configurations are discussed in the following section. The results of this study are compared with earlier studies and conclusions on the influence on turbulence on drag on sharp-edged and rounded tubes at two angles of attack are presented.

3 EXPRIMENTAL FACILITY AND PROCEDURES

Tests were conducted in the upstream aerodynamic working section of the Texas Tech University boundary layer wind tunnel. The wind tunnel is 1.8m wide and 1.2m high with a top speed of approximately 40m/s. The models were actual sections of D=S=150mm (6") tubes; one with sharp edges, the other with 18mm (3/4") radii corners (r) r/D = 0.12. End plates were fitted according to aerodynamic considerations [6] for such tests and extended 1 side-length dimension upstream and to each side and 3 side-lengths downstream of the model. The length of tube between endplates was 1.01m. Figure 1(a) shows the rounded edge tube mounted in the wind tunnel and Figure 1(b) shows the sharp edged tube.


Figure 1. (a) Rounded edge tube, (b) sharp-edged tube, showing end plate configuration.

A row of 24 pressure taps was placed around the mid section of the rounded tube, 5 on each face and 1 on each corner. 28 taps were placed around the mid section of the sharp edged tube, 7 on each face. Taps were at 25mm centers with end taps at the corner (rounded tube) or 12.5mm from the corner (sharp tube). 18mm steel tubes were glued into the tapings and connected by 200mm, 1.04mm diameter tubes to a Scanivalve Zoc 33*64 pressure transducer module, mounted inside the tube. Reference dynamic and static pressures were obtained from a pitot-static tube mounted in the same plane as the tube at the mid-height of the wind tunnel. All pressures were sampled simultaneously at 300 Hz for 60 seconds.

Measurements were obtained at speeds ranging from 10 to 40m/s. This covered a range of Reynolds Numbers from ~ $1*10^5$ to $4*10^5$, with Reynolds No. defined as:

$$\mathrm{Re} = \frac{\rho D \overline{V}}{\mu} = \frac{\rho S \overline{V}}{\mu} \tag{1}$$

Here ρ and μ are air density and viscosity respectively and D = S is tube side length and the mean velocity of the flow $\overline{V}$.

The mean drag force (F_D) on the tube was estimated from integration of the mean surface pressures (p). A dimensionless drag coefficient (C_D) was obtained based on the tube side length (S) and the mean dynamic pressure in the plane of the measurements ($^1/_2\rho V^2$), (this largely accounts for wind tunnel blockage, which amounted to ~ 8% and was not corrected in any way). The drag coefficient is defined by:

$$C_D = \frac{F_D}{\frac{1}{2}\rho \bar{V}^2 A} = \frac{\Sigma(p\delta A)}{\frac{1}{2}\rho \bar{V}^2 A} = \frac{\Sigma(p\delta s)}{\frac{1}{2}\rho \bar{V}^2 S} \qquad (2)$$

For the 45° wind direction, onto a corner, the projected frontal area is often used to non-dimensionalize the drag force, this amounts to replacing S by √2S in the denominator of Equation 1.

The experiment was undertaken in smooth flow, 0.15-0.4% turbulence intensity (for 12-47m/s respectively), and with a grid upstream (turbulent flow) that generated 12-14% turbulence intensity (for 29 – 10m/s respectively) at the test location. Turbulence measurements were obtained from a TSI constant temperature hot wire anemometer mounted at mid-height of the wind tunnel at the location of the model prior to installation. The grid consisted of timber 2" by 4"s intersecting at 370mm horizontally and 400mm vertically and was approximately 2.4m upstream of the tube as shown in Figure 2.

Figure 2. Tube model in wind tunnel with upstream grid s approximately 2.4m upstream of the tube.

4 RESULTS

4.1 *Sharp and rounded tubes in smooth and turbulent flow at 0°*

Figure 3 shows the measured Drag Coefficient versus Reynolds Number for the smooth and turbulent flow cases for both the sharp-edged and rounded tubes for wind perpendicular to one face (0°). Turbulent flow results are substantially less than the smooth flow counterparts for both the sharp-edged and rounded tubes. This is not surprising, as it is well known that turbulence promotes earlier re-attachment on the sides of bluff bodies after leading edge separation [8]. Reattached flow leads to pressure recovery and consequently less suction in the wake and on the back face of the tube. For the smooth flow and sharp-edges, there is little evidence of Reynolds Number dependency, however as expected there is a trend, at least in the range studied here, of a reduction in drag for increasing Reynolds Number. It is also clear that for the turbulent and sharp-edge case there is a somewhat similar trend, with the hypothesis that turbulence is promoting earlier reattachment at higher speeds leading to a reduction in drag coefficient. The pressure recovery was certainly evident in the pressure measurements.

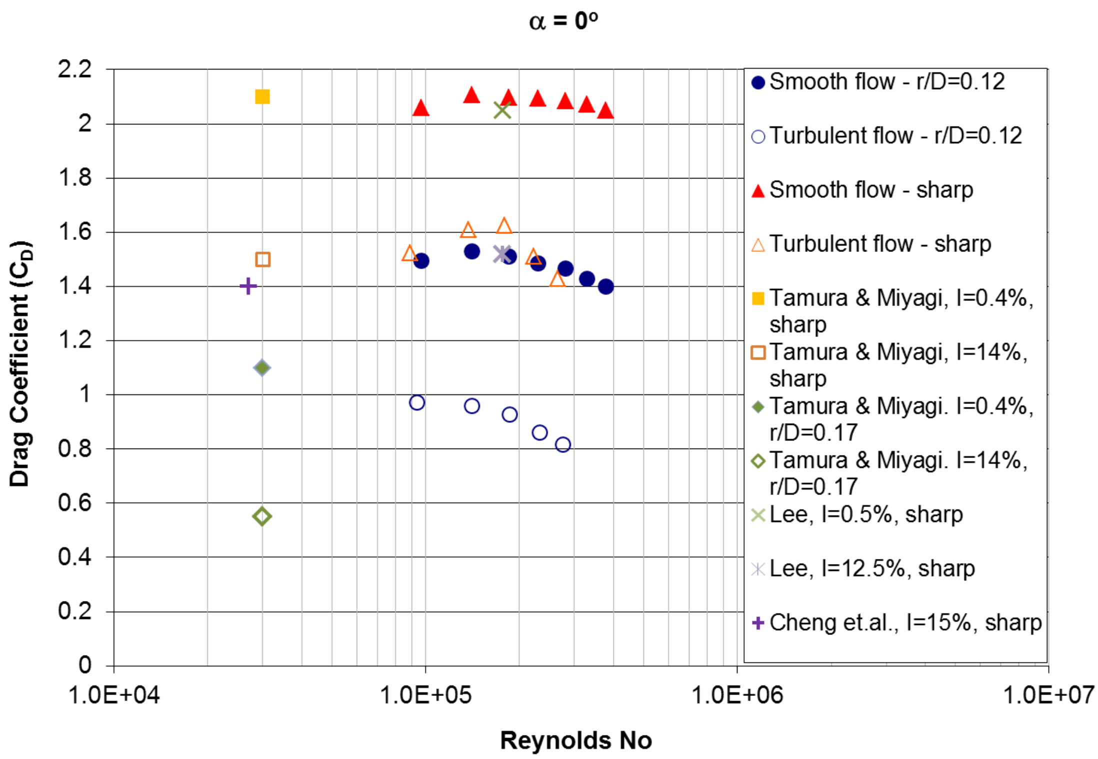

Figure 3. Smooth and turbulent flow mean drag force coefficients for sharp and rounded tubes as a function of Reynolds No.

The smooth flow results obtained in this study are somewhat *larger* than for earlier studies involving sharp-edged and rounded (r/D = 0.125) tubes, as shown in Figure 4. Here the rounded tubes have a C_D of 1.4 - 1.5 while earlier studies indicate ~ 1.2 – 1.3. For the sharp-edges tubes here, C_D were 2.05 – 2.1 while earlier studies have 1.9 - 2.0. The effect of wind tunnel turbulence, blockage, model surface finish and end plates all impact upon the drag coefficient and it is not always clear in the literature, which, if any, of these parameters has been considered or corrected for. The results of James and Vogel [5] were obtained on similar sized tubes

(150mm - 6”) but much shorter, only 380mm long and without endplates. It is likely that this impacted considerably on their drag coefficient measurement [6, 7]. Very little data appears to exist for tubes of this shape in turbulent flow with the work of Lee [9], Cheng et.al. [10], and Tamura et.al. [11] representing the most comprehensive. Only Lee is at comparable Reynolds Number and agreement is good as shown in Figure 3.

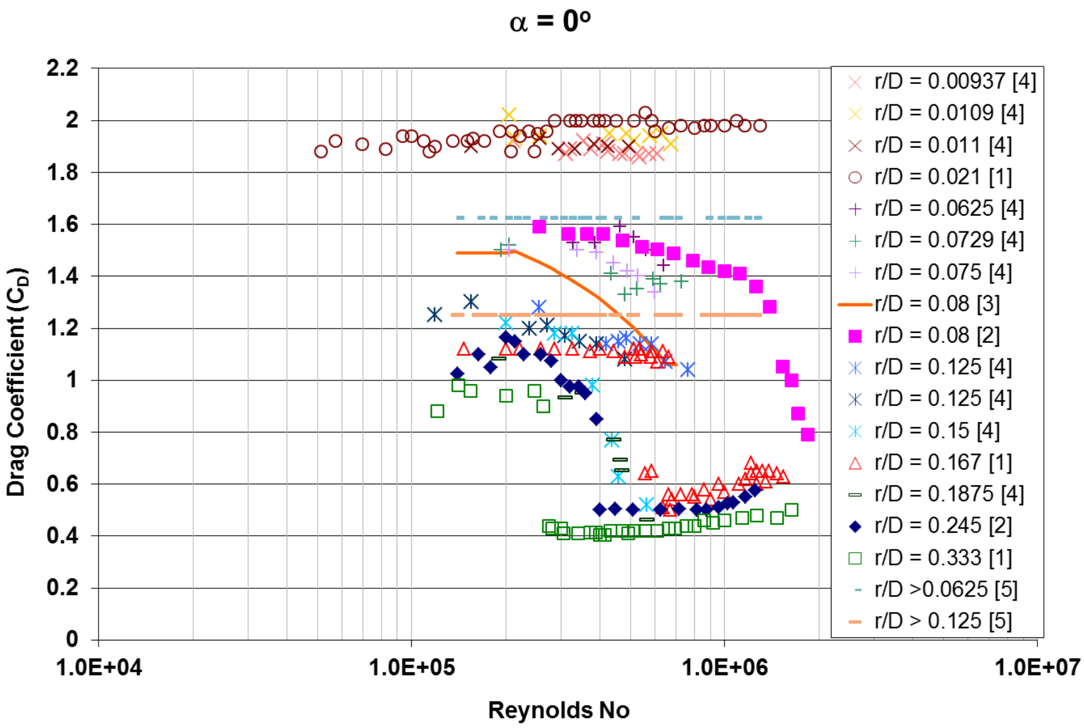

Figure 4. Summary of previous smooth flow results for Drag on rounded tubes as a function of Reynolds No for wind perpendicular to a face.

4.2 *Sharp and rounded tubes in smooth and turbulent flow at 45^o*

Figure 5 shows the Drag Coefficient versus Reynolds Number for the smooth and turbulent flow cases for both the sharp-edged and rounded tubes for wind onto a corner (45^o). Here the drag coefficient is based on the projected frontal area (√2S). This definition of C_D has been arbitrarily adopted as a convention in earlier studies of drag on tubes. Interestingly the turbulent flow results are now very similar to the smooth flow results for both the sharp-edged and rounded tubes. This is because the flow remains attached on the upstream faces and after separation at the corners there is no opportunity for re-attachment on the downstream faces. Once again, for the smooth flow and sharp-edges, there is little evidence of Reynolds Number dependency, however the reduction in drag with increasing Reynolds Number for the other cases studied is in evidence. Again this could be anticipated for the rounded tubes because of the variable separation point. Just why the sharped-edged tube in turbulent flow should exhibit a similar trend, remains unclear, but that turbulence is again promoting increasing curvature of the separating shear layer with increasing mean velocity and leading to a reduction in drag coefficient.

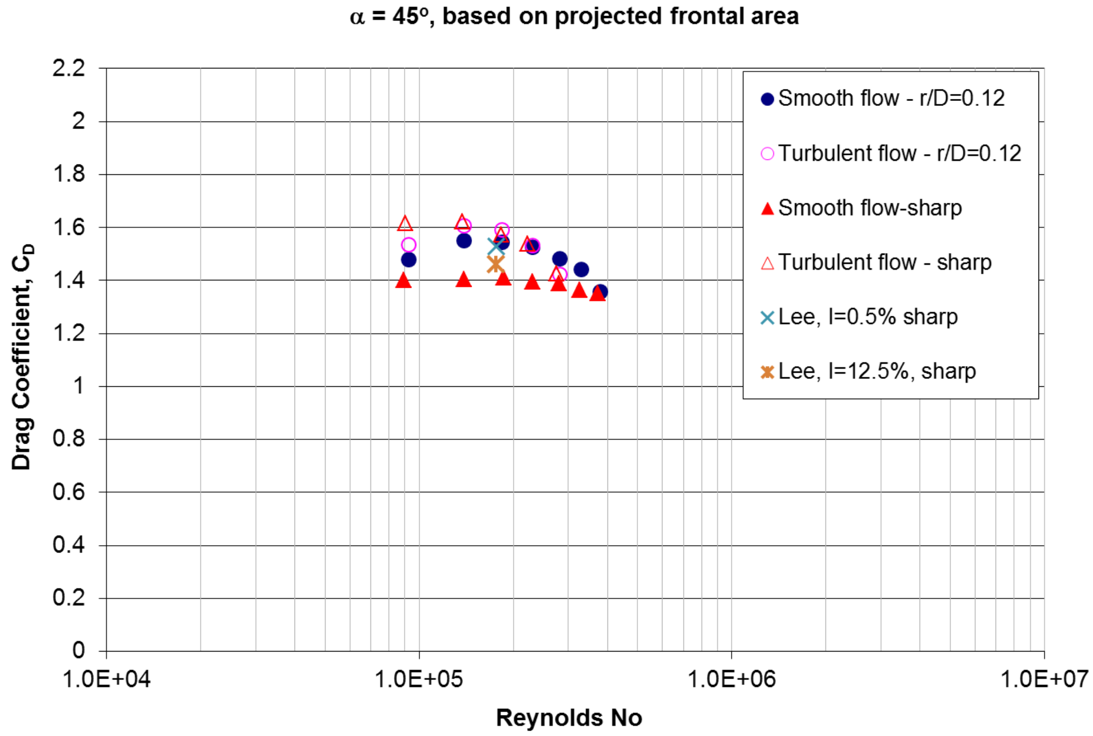

Figure 5. Smooth and turbulent flow mean drag force coefficients for sharp and rounded tubes as a function of Reynolds No.

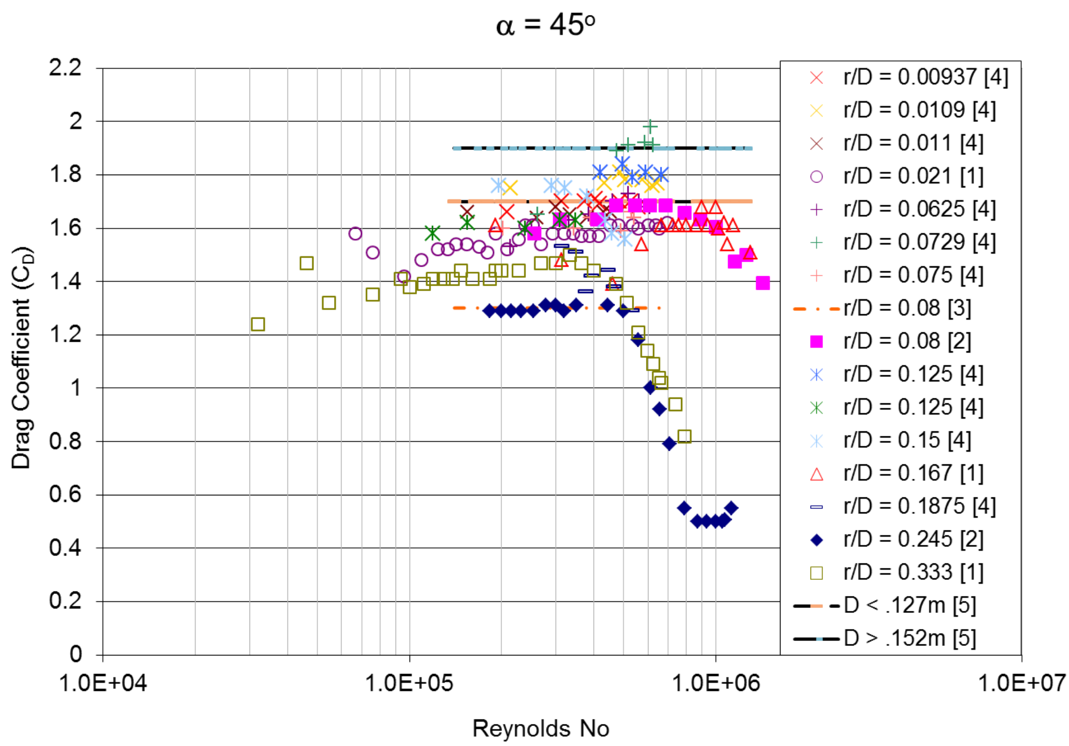

Figure 6. Summary of previous smooth flow results for Drag on rounded tubes as a function of Reynolds No for wind onto a corner. C_D is based on projected frontal area.

The smooth flow results obtained in this study are now *lower* than for the sharp-edged and rounded (r/D = 0.125) tubes, as shown in Figure 6. Here the rounded tubes have a C_D of 1.4 - 1.5 while earlier studies indicate 1.6 – 1.9. For the sharp-edged tube the C_D were 1.4 - 1.6 while earlier studies have 1.6 – 1.7. Once again, the effect of wind tunnel turbulence, blockage, model surface finish and end plates all impact upon the drag coefficient and it is not always clear in the literature, which, if any, of these parameters has been considered or corrected for. As above the shorter length and absence of endplates in the work of James and Vogel [5] likely impacted drag coefficient measurement and is considered a significant reason for the difference between results. The work of Lee [9] remains one of the few sources of the effect of turbulence at high Reynolds Number and at this angle of attack and the present results agree well with his study as shown in Figure 5.

5 SUMMARY

Wind tunnel tests on 150mm (6”) square section tubes with sharp and rounded (18mm) corners in smooth and turbulent flows for two wind directions have been undertaken. The variation of Drag Coefficient with Reynolds Number is reported and is in qualitative agreement with earlier studies, although the current drag coefficient measurements are somewhat larger for wind perpendicular to a face and smaller for wind onto a corner. This may be attributed to deficiencies in some earlier studies in terms of wind tunnel blockage and endplate configuration. It is believed that the results of this study better represent the actual drag coefficient in smooth flow conditions (<0.5% turbulence) because of the range of speeds studied (up to 40m/s) on full-scale tubes that were sufficiently long to avoid end effects. More importantly, the effect of turbulence (~15% intensity) reduces the drag coefficients significantly (up to 50%) for the case of wind perpendicular to a face. This phenomenon has been observed before and is confirmed here over a wider range of Reynolds Number and in particular at turbulence levels much closer to actual flow conditions where these tubes find application. These results should be preferred over higher smooth flow results.

6 ACKNOWLEDGEMENTS

The authors wish to acknowledge the Wind Science and Engineering Research Center at Texas Tech University where this work was undertaken and the Valmont Industry Group for sponsoring this work.

7 REFERENCES

[1] N.K. Delany & N.E. Sorensen, Low speed drag of cylinders of various shapes, NACA Technical Note 3038, Ames Aeronautical Laboratory, November 1953.

[2] E.C. Polhamus, Effect of flow incidence and Reynolds Number on low speed aerodynamic characteristics of several noncircular cylinders with applications to directional stability and spinning, NASA Technical Report R-29, Langley Research Center, September 1957.

[3] J.F. Marchman, Wind tunnel tests of square tube, VPISU Aerospace Engineering Report, July 1971.

[4] W.D. James & J.M. Vogel, Variation of section drag coefficient with variation of Reynolds Number for square cylinders with various corner radii, Report for Valmont Industries, June 1996.

[5] AASHTO Standard for Highway Signs, Luminaires & Traffic Signals, 4th Ed, 2001.

[6] E.D. Obasaju, On the effects of end plates on the mean forces on square sectioned cylinders, J. Wind Engng. & Ind. Aerodyn., 5, 179-186, 1979.

[7] C. Farell & S.K. Fedeniuk, Effect of end plates on the flow around rough cylinders, J. Wind Engng. & Ind. Aerodyn., 28, 219-230, 1988.

[8] P. Saathoff & W.H. Melbourne, Effects of free-stream turbulence on streamwise pressure measured on a square-section cylinder, J. Wind Engng. & Ind. Aerodyn., 79, 61-78, 1999.

[9] B.E. Lee, The effect of turbulence on the surface pressure field of a square prism, J. Fluid Mech. 69 263-282, 1975.

[10] C.M. Cheng, P.C. Lu, & R.H. Chen, Wind loads on square cylinder in homogeneous turbulent flows, J. Wind Engng. & Ind. Aerodyn., 41-44, 739-749, 1992.

[11] T. Tamura & T. Miyagi, The effect of turbulence on aerodynamic forces on a square cylinder with various corner shapes, J. Wind Engng. & Ind. Aerodyn., 83, 135-145, 1999.